Final Progress Report September 26, 2013

DOE award #: DOE EPSCoR program, grant number: DE-FG02-08ER46502
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Project Title: Influence of Sea Ice on Arctic Marine Sulfur Biogeochemistry in the Community Climate System Model
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Report period: July1, 2008 to June 30, 2013
Approved budget amount: $343,366
Participating National Laboratory: Los Alamos National Laboratory (LANL)

Lead cloud offshore Barrow, Alaska. Photo courtesy Bill Simpson.

Abstract:

Global climate models (GCMs) have not effectively considered how responses of arctic marine ecosystems to a warming climate will influence the global climate system. A key response of arctic marine ecosystems that may substantially influence energy exchange in the Arctic is a change in dimethylsulfide (DMS) emissions, because DMS emissions influence cloud albedo. This response is closely tied to sea ice through its impacts on marine ecosystem carbon and sulfur cycling, and the ice-albedo feedback implicated in accelerated arctic warming. To reduce the uncertainty in predictions from coupled climate simulations, important model components of the climate system, such as feedbacks between arctic marine biogeochemistry and climate, need to be reasonably and realistically modeled. This research first involved model development to improve the representation of marine sulfur biogeochemistry simulations to understand/diagnose the control of sea-ice-related processes on the variability of DMS dynamics. This study will help build GCM predictions that quantify the relative current and possible future influences of arctic marine ecosystems on the global climate system.

Our overall research objective was to improve arctic marine biogeochemistry in the Community Climate System Model (CCSM, now CESM). Working closely with the Climate Ocean Sea Ice Model (COSIM) team at Los Alamos National Laboratory (LANL), we added

sea-ice algae and arctic DMS production and related biogeochemistry to the global Parallel Ocean Program model (POP) coupled to the LANL sea ice model (CICE). Both CICE and POP are core components of CESM. Our specific research objectives were: 1) Develop a state-of-the-art ice-ocean DMS model for application in climate models, using observations to constrain the most crucial parameters; 2) Improve the global marine sulfur model used in CESM by including DMS biogeochemistry in the Arctic; and 3) Assess how sea ice influences DMS dynamics in the arctic marine environment and predict how it will do so in the future.

Brief description of accomplishments during reporting period:

(1) Implemented IARC ice ecosystem model in CICE

The project began by implementing our ice ecosystem model in CICE and running the model as in Hunke and Bitz (2009) configured with a 20m-slab ocean. The CICE ecosystem model results from year 1992 were analyzed to assess the annual cycle and spatial variability of ice algal production and biomass on large scales before the recent dramatic sea ice decline (Deal et al., 2011). This manuscript presents the first ever published pan-Arctic ice ecosystem model. The work is an important first step toward modeling Arctic DMS biogeochemistry because sea ice algae are among the major producers of the DMS precursor, dimethylsulfoniopropionate (DMSP).

The CICE ecosystem model reproduces observed seasonality and large-scale spatial patterns within arctic sea ice (Figure 1; Deal et al., 2011). Simulations show that the Bering Sea is the most productive of all Arctic regions on an annual basis due to high daily ice algal production rates. This is explained by the high inorganic nutrient concentration of seawater in this region compared to other regions, in particular the oligotrophic central Arctic Ocean. Recent measurements show the highest standing crop of Arctic sea ice algae occurs in the Bering Sea (Gradinger et al., 2012).

In the model, ice growth rate controls nutrient availability and thereby productivity, while ice-melt rate determines release of ice algae into the water column. Rapidly decreasing ice algal productivity is followed closely by a decline in biomass over large areas suggesting the potential for a strong pulse of DMS(P) into the water column and atmosphere.

The CICE ecosystem model advances the role of sea ice algal C flux and biogeochemical cycling in global climate models. It thus provides a model framework on which to add other important biochemical cycling in sea ice (e.g. Hg, halides, organic aerosol precursors including DMS).

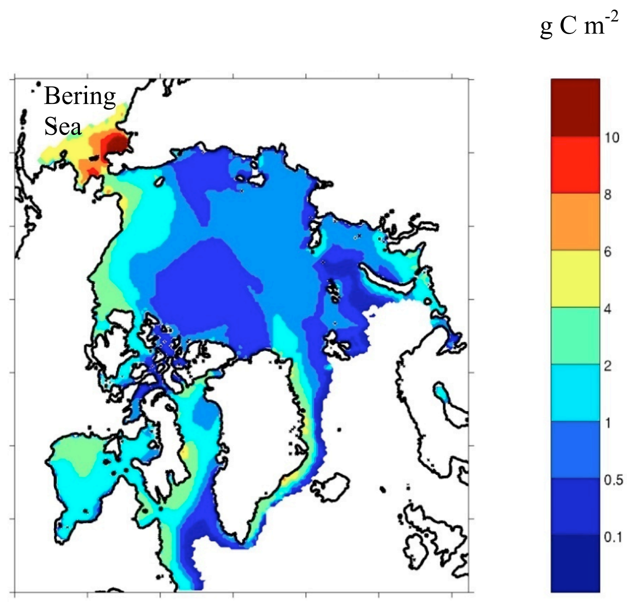


Figure 1. Simulated annual primary production within arctic sea ice for 1992 (Deal et al., 2011).

(2) Coupled CICE ecosystem model to POP DMS ecosystem model

We have coupled the CICE ecosystem model to POP enabling nutrient, and dissolved and particulate organic matter exchanges and interactions between sea ice and ocean model components. Surface seawater supplies the nutrients to the sea ice that sustain the ice-associated food web and biogeochemical cycles.

A DMS ecosystem model is only as good as the ecosystem model to which it is coupled. We therefore evaluated how well the coupled CICE-POP ecosystem model reproduces observed seawater chlorophyll concentrations and primary production before focusing on improving the Arctic sulfur biogeochemistry. The CICE-POP ecosystem model results and validation have recently been published in *Deep-Sea Research-II* (Jin et al., 2012a). Model simulations show realistic mean seasonal cycles for ice algal production and phytoplankton production. Also, they compare well with decadal-scale observed in situ and remotely sensed changes in primary production from the 1990s to 2007 due to rising temperature and increasing open-ocean area in the western Arctic.

To speed model improvement, we participated in an Arctic Ocean Modeling Intercomparison Project that compared five coupled physical and biological models for the Arctic domain (Popova et al. 2012). We found that the depth of winter mixing, one of the main mechanisms supplying inorganic nutrients over the majority of the AO, was too deep in our model, among others. This may not be detrimental to determining present-day primary productivity, since both light and nutrient limitation are tightly coupled to the presence of sea ice. Essentially, as long as at least one of the two limiting factors is reproduced correctly, simulated total primary production will be close to that observed. We have since improved vertical mixing in the model by using the lead-dependent subgrid scale brine rejection parameterization described in Jin et al. (2012b). Given that remotely sensed observations of chlorophyll (SeaWiFS) are restricted to waters with less than 10% sea ice concentration and terrestrial/river input contaminates the signal in some coastal areas, among other problems (Popova et al., 2012), the model results agree reasonably well with estimates of chlorophyll concentration (Figure 2a and b, respectively). Indeed, an important role for models is to provide information when and where in situ and remotely sensed observations are limited.

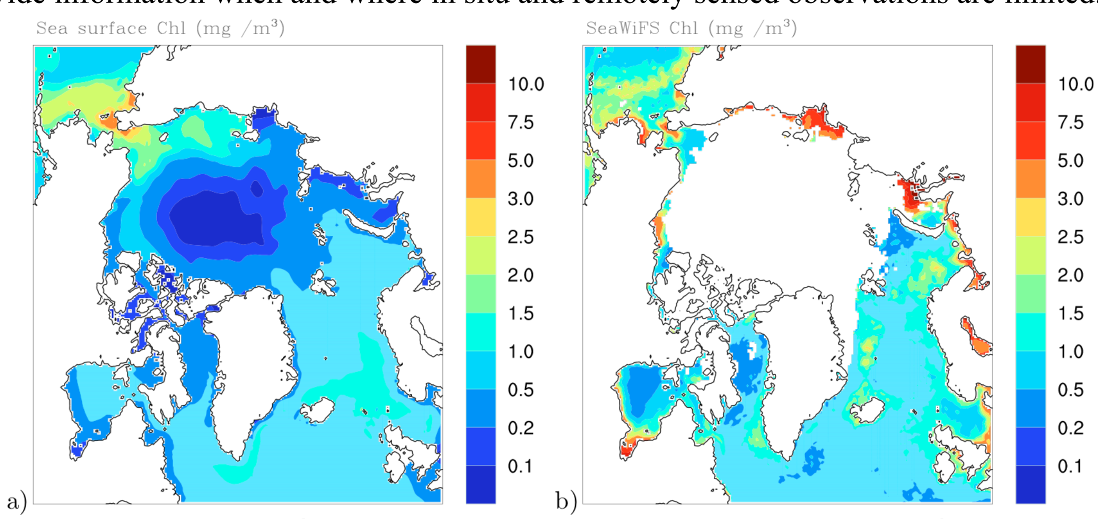


Figure 2. Sea surface chlorophyll averaged over 1998-2007 for (a) model, and (b) SeaWiFS (Jin et al., 2012a).

(3) Developed first-of-its-kind sea ice DMS model

As the CICE ecosystem model was being coupled to POP DMS ecosystem model; we developed a sea ice DMS model. This sea ice DMS model is described in detail in Elliott et al. (2012) as the first-ever numerical model of DMS biogeochemical cycling in sea ice. We approached the sea ice DMS model development from both 1-D local and 3-D global scales. Laboratory tracer studies using stable isotope additions in sea ice (Stefels et al., 2011) allowed us to work within measured ranges of critical DMS loss and production rates to optimize our sea ice DMS model. For the 1-D version we coupled the sea ice DMS model to the 1-D ice-ocean ecosystem model of Jin et al. (2006) and evaluated it using the time series measurements of DMSP in Barrow sea ice (Uzuka et al., 2003). For the 3-D version, we coupled the sea ice DMS model to our CICE ecosystem model and used a compilation of chlorophyll and DMS measurements for model development (Elliott et al., 2012). The same ice algal parameter values are used in both model versions. Simulations suggest that during ice-melt most of the ice algal DMSP is released to the underlying ocean mixed layer. A large fraction of this DMSP becomes dissolved DMSP, which is lysed to DMS.

(4) Improved Arctic S biogeochemistry in CICE-POP DMS ecosystem model for CESM

The CICE-POP DMS ecosystem model is a global model and improvements for the Arctic should not be made at the expense of other regions. This is critical to meet our long-term goal of having the DMS model improvements included in CESM. Improvements stem from the model implementation of ice algae and the ice algal DMS source, as well as from the coupling of CICE to POP that has provided ice extent and ice area simulations that closely match remotely sensed sea ice observations (Jin et al., 2012a). The changes that we made to Elliott's (2009) ocean DMS model within POP do not compromise results at lower latitudes. We modified this model so that *Phaeocystis* no longer appears as a dominant phytoplankton type in the Arctic Ocean in agreement with current knowledge of Arctic phytoplankton species (Tremblay and Gagnon, 2009). Another major modification included changes to the temperature and chlorophyll concentration dependence of DMS production (i.e., "gyre decrement function" in Elliott (2009)). Now when chlorophyll concentrations in the Arctic are < 0.1 mg m^{-3} the model does not ramp up DMS production as an indirect effect of light/oxidant stress. These model additions and modifications, among others, as well as the DMS model validation and sensitivity studies presented below, are discussed in Deal et al. (in preparation).

We now have model results for pan-Arctic DMS and DMSP concentrations in ice and seawater extending from 1958 through 2009. The magnitude of DMSP and DMS concentrations in sea ice and seawater agree well with limited observations. A snapshot of simulated seawater DMS concentrations (Figure 3) shows ~1-3 nM DMS in seawater under the ice, higher concentrations in the seasonal ice zone, and highest values along ice edge (white contour line).

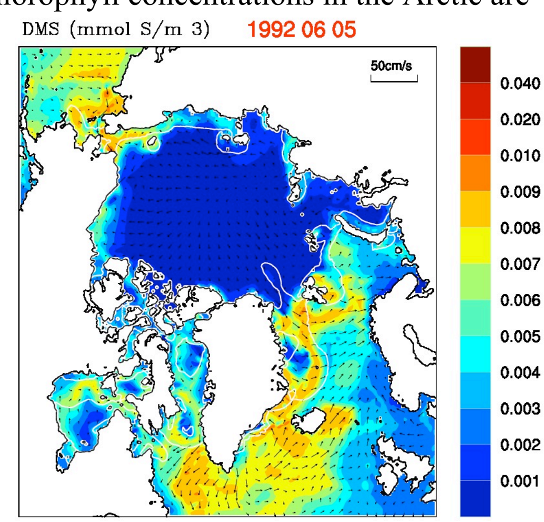


Figure 3. Simulated surface seawater DMS concentrations. Units of 0.001 mmol S m^{-3} = 1 nM DMS (Deal et al., in preparation).

(5) Evaluated DMS model results using available observations

DMS model results are compared with DMS observations from NOAA PMEL DMS database http:/saga.pmel.noaa.gov/dms (Lana et al., 2011). The number of observations available at each location in the Arctic is displayed in Figure 4a. DMS is highly variable in space and time, and information from point measurements is not directly comparable to global or regional model output. We briefly present here examples from a combination of qualitative and quantitative assessment approaches that have each their own strengths and weaknesses.

Observational DMS data gridded to one degree for summer months (July, August, September) allow for a climatological comparison with the model data, which has a resolution of one degree. Shown below are the gridded surface seawater DMS concentrations observed in summer (Figure 4b) and the summer mean model results (Figure 4c). The model captures the overall spatial pattern and produces reasonable surface seawater DMS concentrations.

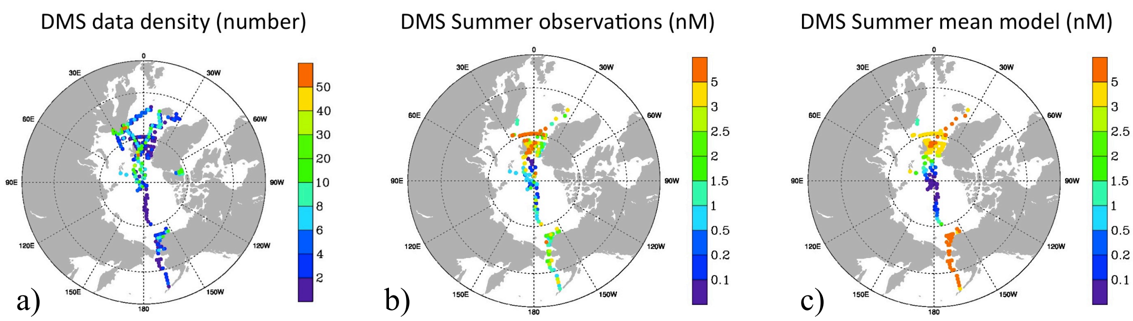


Figure 4. Sea surface DMS (a) observations available, (b) gridded observation values in summer, and (c) model values in summer for all years 1958-2009.

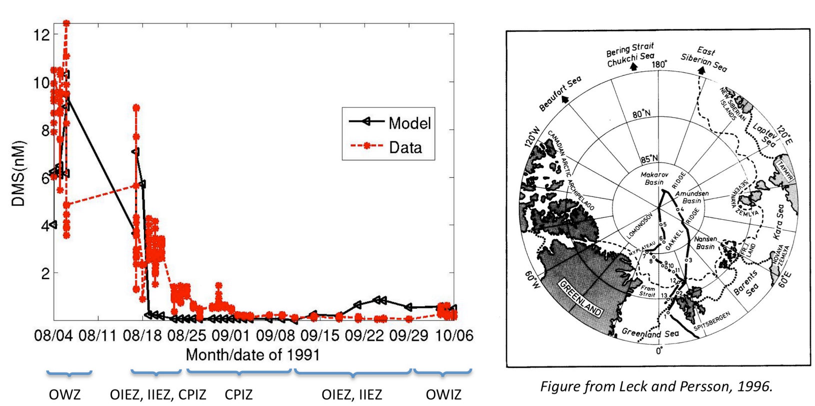
To assess model skill we computed the standard deviation (STD), median value of the ratio of measured to modeled values (Fmed), root mean square deviation (RMSD), and mean error (ME or bias) by comparing measurement values with the model value for the same location, year, and date (Table 1).

Model version	STD	F_{med}	RMSD	ME (Bias)	N
This study	0.35	0.52	0.45	-0.28	1724

Table 1. Model skill statistics computed for DMS model results with respect to in situ DMS observations (log-log) in the surface Arctic Ocean for all years 1958-2009.

A comparison of DMS model results to in situ DMS data along cruise track (Leck and Persson 1996) across ice edge to 90 degrees north and back shows good agreement (Figure 5).

Figure 5. A comparison of DMS observations along a cruise track (Leck and Persson, 1996) and model results. Observations made in open water zone OWZ, open ice edge zone OIEZ, inner ice edge zone IIEZ, and closed pack ice zone CPIZ. Dashed lines indicate most southerly and northerly ice edge locations during expedition.



(6) Predictions of how sea ice influences seawater DMS dynamics in the Arctic

Once the model was validated using available observations for chlorophyll concentration, primary productivity, and DMS(P) in ocean waters and sea ice, we used the model to conduct sensitivity studies to investigate the influence of sea ice on surface seawater DMS concentrations. One of the model experiments we performed was running the model with and without sea ice biogeochemistry (i.e., ice algae and DMS(P) production in sea ice). Model results suggest that ice algae are an important source of seawater DMS, particularly in the Bering Sea in April, and shelf seas surrounding central Arctic Ocean in May (Figure 6). Ice algal DMSP export from sea ice is key.

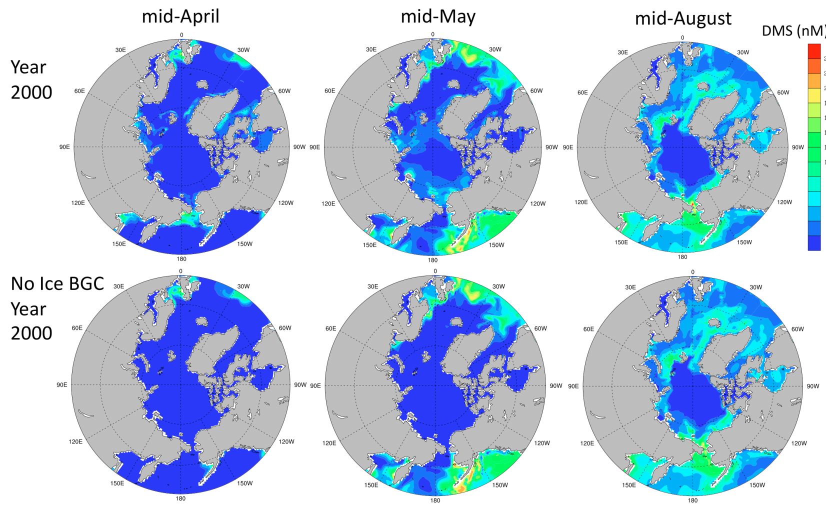
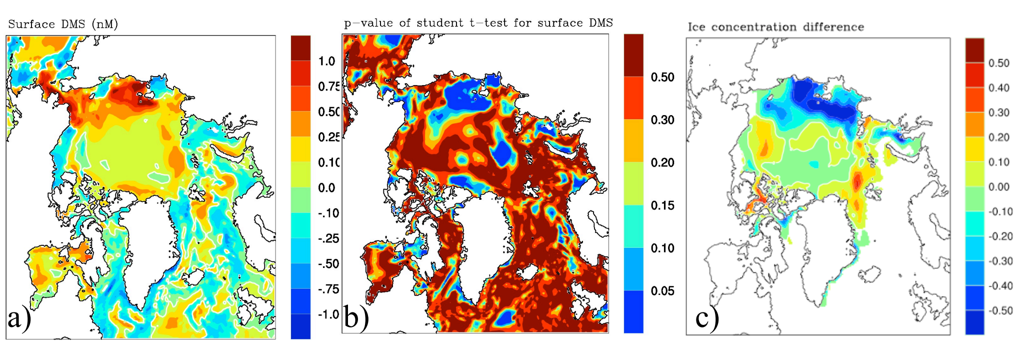


Figure 6. Simulated surface seawater DMS concentrations for year 2000 with (upper) and without (lower) sea ice biogeochemistry.

In another model experiment, we compared surface seawater concentrations simulated for low ice (warm years) versus high ice years (cold years) across the Arctic. Figure 7a shows higher surface seawater DMS concentrations in warm years across most of the Arctic, which suggests an enhancement of DMS emissions. The student t-test reveals that statistically significant differences in surface seawater DMS concentrations (p-value < 0.05; Figure 7b) coincide for the most part with areas of highest ice concentration difference (Figure 7c). For example, the largest of these areas off the north coast of Russia occurs where the simulated ice concentration decreased by 50%.

Figure 7. Modeled (a) sea surface DMS concentration for the mean of low ice (2002, 2003, 2005-2007) minus high ice (1998-2001, 2004) years, (b) p-value of student t-test, and (c) ice concentration difference.



These sensitivity studies further highlight the need for more DMS observations in the Arctic sea ice environment. There are no observations available to verify the large contribution of ice algal DMS to surface seawater in the Bering Sea in April or the model suggested increases due to diminished sea ice off the coast of Russia. Yet, these areas are where our simulations predict the most pronounced changes in DMS emissions are likely to occur. These omissions illustrate another important role of models, to guide field campaigns by pointing out critical areas or processes that require measurements.

In conclusion, this work prepares the CESM community for more realistic simulations that include DMS-cloud albedo-climate feedbacks. The sea ice ecosystem model code including sulfur and nutrient cycling as described in Elliott et al. (2012) is scheduled for public release in 2013 http://oceans11.lanl.gov/trac/CICE/wiki/CiceDev

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Deal, C.J., M. Jin, S. Elliott, E. Hunke, M. Maltrud, and N. Jeffery, Large-scale modeling of primary production and ice algal biomass within arctic sea ice, *Journal of Geophysical Research-Oceans*, 2011.

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In Preparation Publication Referencing DOE EPSCoR Support:

Deal, C.J., S. Elliott, M. Jin, E. Hunke, M. Maltrud, and J. Stefels, The influence of sea ice on DMS dynamics in the Arctic Ocean, in preparation.

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People who worked on the project:
Clara Deal, Research Associate Professor; partial support, 13.6% per year for five years
Meibing Jin, Research Associate Professor; partial support, 9.0% per year for five years
Bindu Madhavi Gadamsetty, graduate student; full support, 100% per year for one year
Grant Richard Woodrow Humphries; graduate student, partial support, 44.7% per year for one and one half years
Candace O'Connor, Scientific Editor; partial support, 2.2% per year for one half year

Other support (current and pending, federal and non-federal): Listings of current and pending support for Deal and Jin are attached (Deal C & P.xls and Jin C & P.xls). Jin's NSF project focuses on ocean mixing processes and the implications on climate models. This work benefits the DOE EPSCoR project but it does not overlap because it does not include biogeochemical modeling. The NERC-funded project will utilize present-day and future pan-Arctic DMS sea-to-air flux generated from our CICE-POP DMS ecosystem model. These DMS emissions will serve as input for a global atmospheric chemistry model to study feedbacks between clouds, surface energy budget, and sea ice.